# Overview of Ultra-Reliable and Low-Latency Communications in Vehicle-to-Everything

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## I. Introduction

Vehicle-to-Everything (V2X) communications are being studied to support autonomous driving, road safety, and efficient traffic services, all of which are major changes in the future automobile industry. V2X communications can achieve these significant changes by enabling information exchange between vehicles, infrastructure and pedestrians (see Fig. 1). Recently, with the standardization of cellular-based V2X, there had been a great improvement in reliability and communication range. Through this performance improvement, various V2X services are being proposed. Safety-related services can help prevent car accidents and non-safety-related services can provide more efficient driving routes. Also, autonomous driving services can provide convenience and comfort for the driver.

However there are several requirements for V2X services to run. Among the requirements, latency is important. This is because the safety level decreases as the delay in receiving safety information of the V2X system increases. This means that delays in information in V2X communications could result in serious car accidents and injuries. The most strict requirements of V2X services are 10ms latency with the 1e-5 block error rate (BER).

In this paper, we provide an overview of studies to achieve those latency requirements. To be specific, we first look for the standards of V2X. We then explain the V2X operating modes and latency requirements for V2X services. Lastly we present the approaches to achieve ultra-reliable and low-latency communication (URLLC) in V2X and then conclude the paper.

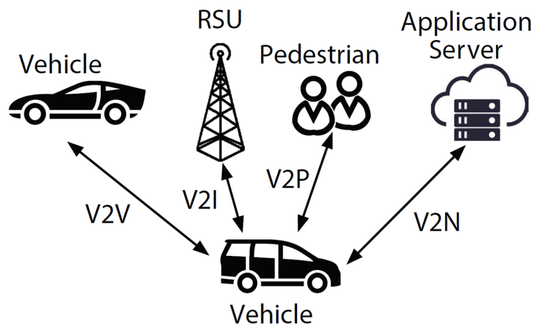


Fig. 1: Four types of V2X application support in 3GPP (i.e., V2V, V2P, V2N and V2I)

## II. Standardization of V2X

In this section, we provide a brief overview of three standardizations in V2X, namely, DSRC, C-V2X, and 5G NR V2X.

### A. DSRC (IEEE 802.11p)

Dedicated short range communications (DSRC) technology, that uses WiFi-based physical, and MAC layer protocol, was standardized by IEEE and European Telecommunications Standards Institute (ETSI). IEEE 802.11p is the default standard that defines the functionalities of the physical, and MAC layers to be used by the DSRC technology. The IEEE 802.11p standard suffers from several shortcomings, which include low data rate at high vehicle densities and packet loss due to hidden terminals. Recently, work has started on the new standard, named IEEE 802.11bd, to overcome the shortcomings of the IEEE 802.11p standard. In this section, we briefly introduce the IEEE 802.11p standards.

IEEE 802.11p is a modified version of the IEEE 802.11 that also known as WiFi standard and works for high-mobility vehicular scenarios. The physical layer of IEEE 802.11p uses orthogonal frequency-division multiple access (OFDMA) with a channel bandwidth that is reduced to half that of IEEE 802.11, thus doubling the OFDMA symbol duration. This was done to handle large delay spread and inter-symbol interference in a vehicular network. The data rate of IEEE 802.11p was also halved from that of IEEE 802.11. The peak data rate offered by the IEEE 802.11p standard is 27 Mb/s.

The MAC layer of the IEEE 802.11p standard is based on carrier sense multiple access with collision avoidance (CSMA/CA). By using contention-based channel access, CSMA/CA manages simultaneous transmissions by vehicular sensors. This allows emergency messages to be transmitted with a shorter contention time. [1]

### B. C-V2X

Cellular Vehicle-to-Everything (C-V2X) technology based on Long-Term-Evolution (LTE) was standardized by 3GPP. In C-V2X, the problem of data rate has been solved by using LTE system, but there is a strict latency requirement for safety related V2X services. Therefore, C-V2X systems consider latency to be the most important performance metric, while conventional cellular systems consider system throughput to be the most important performance metric. The reasons for these are as follows: First, the level of safety decreases as the delay in receiving safety information increases in V2X systems. While a delay in multimedia information may cause a movie to pause temporarily, delayed information in V2X communications could result in serious car accidents and injuries. Second, the volume of data transmission in V2X communication is much smaller than that in general cellular systems. Sensing information or safety notifications transmitted via a V2X link can be carried in a small packet. Hence, high throughput data transmissions are less important in V2X systems. [2]

The C-V2X standard introduced two types of communications: network communications using the Uu interface (the radio interface between the user equipment and the eNodeB) and direct communications using the sidelink channel over the PC5 interface. Network communications operate over licensed spectrum, and messages are relayed to a vehicle's user equipments (UEs) using evolved eNodeB. In contrast, direct communications occur in the 5.9 GHz spectrum, allowing vehicles to directly exchange information. Furthermore, two new D2D transmission modes (mode 3 and mode 4) were introduced, that can support low-latency vehicular services.

The physical layer of C-V2X uses FDM resource multiplexing, single-carrier frequency-division multiple access (SC-FDMA) and works on both 10 MHz and 20 MHz bandwidth. The turbo codes and SC-FDM waveform used in V2X can achieve a longer range or more reliable performance at the same range as compared to DSRC-based V2X communication. A resource block (RB), that can be allocated to a vehicle, is 180 kHz wide in frequency (12 sub-carriers of 15 kHz). The C-V2X MAC layer uses the Sensing-Based Semi-Persistent Scheduling (SB-SPS) protocol, which consists of two parts: sensing and semi-persistent scheduling.

### *C. 5G NR V2X*

There are two wireless technologies that support connected vehicles, DSRC, and C-V2X. However, the current standards (e.g., the IEEE 802.11p and LTE) do not support the quality of service (QoS) required for advanced autonomous driving service and fail to provide consistent high data rate transmissions. To address such deficiencies, new standards, that using 5G NR network, are currently being developed to support future autonomous driving service. The aim of the 5G NR V2X standard is to support advanced services that require ultra-reliability and ultra-low latency. As C-V2X is already in the deployment phase, future vehicles will have both C-V2X and 5G NR V2X technologies coexisting with each other.

The key changes have been considered by 5G NR V2X in the physical layer.

- **Sidelink Modes:** 5G NR V2X defines two sidelink modes (mode 1 and mode 2), which are similar to mode 3 and mode 4 in C-V2X except with some changes. In mode 1, vehicles directly communicate with each other within the coverage range of the base station gNodeB, which allocates resources. A key enhancement in mode 1 is that vehicles should send location and beam information to the gNodeB so that it can allocate resources with improved spatial reuse. Mode 2 allows D2D vehicular communications where resources are allocated autonomously. A noticeable addition in 5G NR V2X is that various submodes of mode 2 are also defined where vehicles can assist each other in resource allocation by sharing resource occupation and channel quality information. Such feedback improves the autonomous resource allocation mechanism. Furthermore, for groupcast communications, a group leader vehicle can manage resource allocation on behalf of the group.

- **Fast Sidelink Scheduling:** In C-V2X, a vehicle that needs to schedule a sideLink (SL) resource first needs to send a scheduling request (SR) to the gNodeB to get a single upLink (UL) resource. After this step, the vehicle again sends a buffer scheduling request (BSR) on the allocated uplink resource to the gNodeB, which then schedules multiple sidelink resources for data transmission. To reduce the latency, 5G NR V2X introduces a fast SL scheduling mechanism where sidelink resources are scheduled in a single step by using the Uplink Control Information (UCI) message containing all the sidelink resource information.

5G NR V2X makes the following key modifications in the MAC layer.

- **Unicast and Groupcast Communications:** While C-V2X allows only broadcast communications, 5G NR V2X enables unicast and groupcast communications. Separate frame formats are yet to be defined by 5G NR V2X to support unicast and groupcast communications.

- **Mini-Slot and Multi-Slot Allocation:** In C-V2X, only fixed sized slots can be scheduled. This causes slots to be wasted if the packet size is too small. To address this issue, the concept of minislots (slots with no fixed start time and end time used for flexible transmissions) has been introduced in 5G NR V2X. Similarly, for large packets multi-slot is possible, which aggregates several time slots, resulting in better slot utilization.

- **Adaptive Sensing Window:** 5G NR V2X adapts the sensing window based on vehicular mobility. In a highly mobile scenario, the sensing window should be reduced as resource information becomes outdated quickly. Moreover, 5G NR V2X recommends skipping the RSSI averaging procedure while selecting resources in C-V2X. By skipping the procedure, fast resource allocation is possible. For aperiodic traffic, short-term sensing similar to that used in WiFi is suggested. Long-term sensing does not work well because arrival of new packets cannot be predicted for aperiodic traffic.

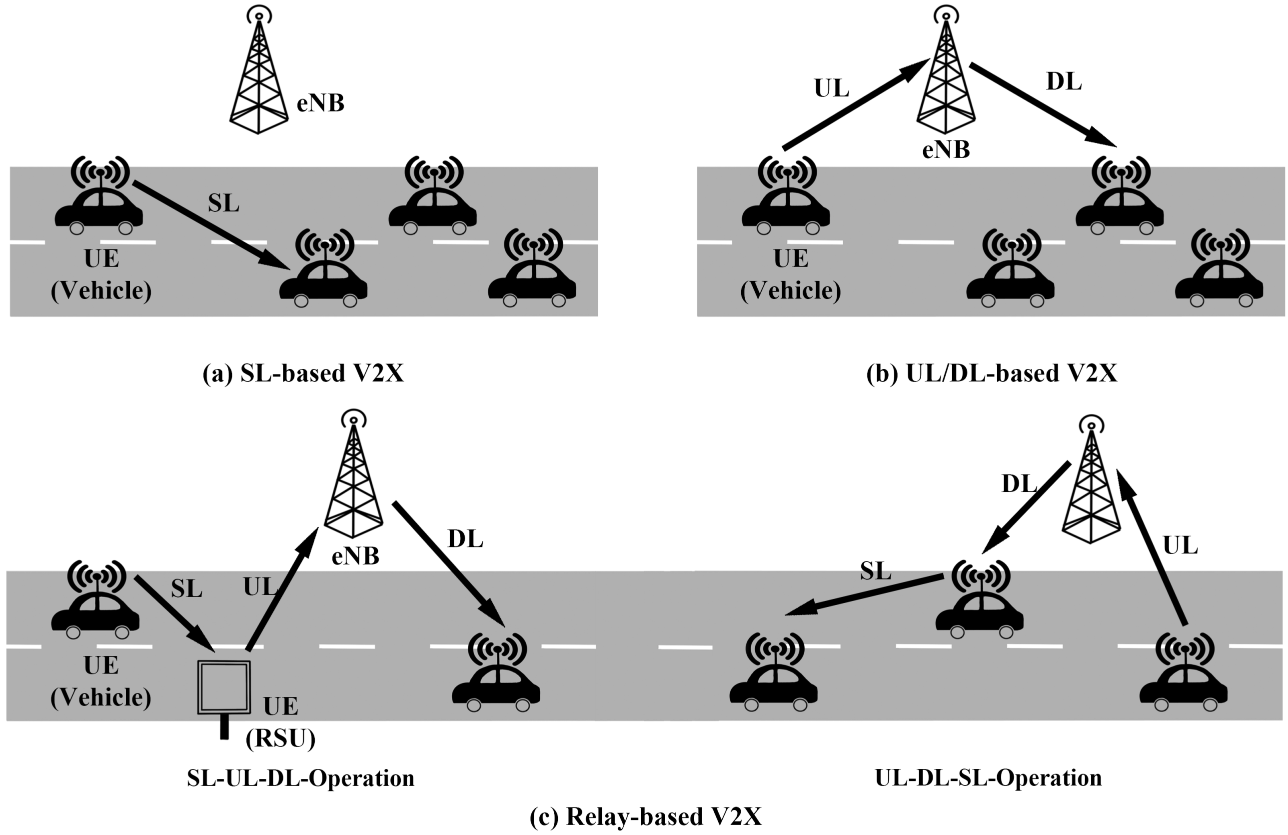


Fig. 2: Modes of operation of V2X communications: (a) operating mode over SL, (b) operating mode over UL/DL, and (c) operation mode using relay transmissions.

## III. Operating Modes and Latency Requirements of V2X

### A. *Operating Modes of Cellular V2X*

The cellular-based V2X communication system operating modes shown in Fig. 2 are as follows: (a) sidelink (SL)-based V2X, (b) uplink (UL)/downlink (DL)-based V2X and (c) relay-based V2X.

The SL-based V2X in Fig. 2(a) is referred to as PC5-based V2X in 3GPP. In SL-based V2X, vehicles directly exchange their information by one-hop transmission. In this mode, the transmitter sends information about location, velocity, traffic, etc. to one or more receivers directly. Since this mode operates in a broadcast manner, the same data can be transmitted efficiently to multiple nodes in a common resource. In this mode, the latency mainly occurs while establishing the uplink connection and resource allocation.

Fig. 2(b) shows the UL/DL-based V2X mode, also referred to as Uu-based V2X in 3GPP. In this V2X mode, two transmission hops must be made when exchanging information between vehicles. In this case, the information is first received at evolved node B (eNB) in an UL, then forwarded to destination receivers in a DL. For transmitting the information in the DL, appropriate DL protocols can be selected from among unicast, the multimedia broadcast multicast service (MBMS), or single cell point-to-multipoint (SC-PTM).

Fig. 2(c) is the relay-based V2X mode. This mode is not specifically named in 3GPP. In this mode, vehicles send their information over more than two hops. With multi-hop transmission, the information signal goes through road side units (RSU) and cellular networks. A transmitter can send V2X data to other user equipment (UE) or RSUs through the SL. The UEs that receive the data forward it to the eNB through the UL. The eNB then transmits the data to other UEs in the DL. This takes at least three hops, as depicted in Fig. 2(c). As shown on the right side of Fig. 2(c), the data transmission path can also be UL-DL-SL, depending on the location of the RSU and eNB. The relay-based V2X mode cannot help consuming the longest time for data transmission, resulting in the worst latency while the multi-hop transmission lengthens the communication distance. [3]

### B. *V2X Services and Requirements*

There are several requirements for V2X services to run. For example, vehicle's speed, communication range, reliability, latency, etc. V2X service is available when the vehicle's absolute speed is less than 160 km/h, and when the relative speed is less than 280 km/s. The communication range must be greater than

| Service Type | Use Cases | Description | Latency Requirement |
|---|---|---|---|
| Safety-related services | Forward collision warning (FCW) | The FCW is intended to warn the driver of the host vehicle (HV) in case of an impending rear-end collision with a remote vehicle (RV) ahead in traffic in the same lane and with the same direction. | 100ms |
| | Control loss warning (CLW) | The CLW application enables an HV to broadcast a self-generated loss of control event to surrounding RVs. | 100ms |
| | Emergency warning | The emergency vehicle warning service enables each vehicle to acquire the location, speed and directional information of a nearby emergency vehicle. | 100ms |
| | Emergency stop | This use case describes how V2V communications are to be used in the case of an emergency stop in order to trigger safer behavior in other cars that are in close proximity to the stationary vehicle. | 100ms |
| | Queue warning | Using the V2I Service, relevant queuing information can be made available to other drivers beforehand. This minimizes the likelihood of crashes and allows drivers to take mitigation steps. | 100ms |
| | Road safety services | V2X messages are delivered from one UE that supports V21 Services to other UEs that also support V21 Services via a Road Side Unit (RSU), which may be installed at the road side. | 100ms |
| | Pre-crash sensing warning | The pre-crash sensing warning provides warnings to vehicles in the event of an imminent and unavoidable collision by exchanging the attributes of the vehicle when a crash is anticipated. | 20ms |
| Automated driving-related services | Automated overtake | Executing safe overtaking maneuvers requires cooperation among vehicles travelling in multiple lanes in order to create the necessary gap to allow the overtaking vehicle to quickly merge into the lane corresponding to its direction of travel in time to avoid a collision with an oncoming vehicle. | 10ms |
| | Cooperative collision avoidance | Collisions between two or more vehicles are prevented by controlling the velocity and displacement of each vehicle along their path without creating hazardous conditions for other vehicles that are not directly involved. All involved vehicles undertake optimal action and apply in a cooperative manner. | 100ms |
| | High density platooning | High Density Platooning, i.e., the creation of closely spaced multiple-vehicle chains on a highway, has multiple benefits, such as fuel saving, accident prevention, etc. | 10ms |
| | See-through | For the safety of pedestrians who are crossing the road in front of an HV, the camera in the HV detects the situation and shares information regarding the pedestrian with RVs to the rear of the HV. | 50ms |

TABLE I: V2X service use cases and latency requirements

the braking distance due to the communication delay. That is, when a collision is detected, a sufficient communication range must be provided to avoid collision. Reliability is required that can be transmitted without retransmission at effective distances and limited latency.

Finally, the most important requirement, latency, should be shorter than the required end-to-end latency for each service (e.g., 100 ms, 50 ms, 20 ms, and 10 ms). V2X services can be categorized into three groups: 1) safety-related services, 2) non-safety services, and 3) autonomous driving-related services.

- **Safety-related services**: Safety-related services are concerned with real-time safety messages, such as warning messages (e.g., abrupt brake warning message) to reduce the risk of car accidents. In these type of services, timeliness and reliability are considered to be key requirements. For the safety-related services, if we consider the frequency of periodic messages (e.g., from 0.6 s to 1.4 s), then the maximum allowable end-to-end latency must not exceed 100 ms. In fact, depending on the service type, the latency requirement may even be less than 100 ms, (e.g., 20 ms for a pre-crash sensing warning).

- **Non-safety-related services**: Non-safety-related services are intended to optimize the traffic flow on the road so that travel time is reduced. Thus, these services enable a more efficient and comfortable driving experience with no stringent requirements in terms of latency and reliability.

- **Autonomous driving services**: Autonomous driving-related services are now being developed as key transformations begin to occur in the automotive industry. These automated driving-related services require more rigorous latency, data rate, and positioning accuracy requirements. Therefore, the latency requirements for automated driving-related services are more stringent than those required for safety-related services. For example, automated overtaking or high density platooning services have a 10 ms requirement.

Since the scope of this paper is the latency issue in V2X communications. Table 1 lists the V2X service use cases and the corresponding latency requirements.

## IV. Challenges and Approaches to achieve URLLC

V2X services face challenges due to stringent latency requirements, along with high reliability for V2X services. So there are various approaches going on to achieve these requirements. In this section we introduce research papers that have worked to achieve URLLC in V2X communications.

### A. Resource Allocation Schemes

In the paper [4] the author provides V2V resource allocation scheme to reduce the delay while resource allocation. In this scheme, every vehicle periodically checks its packet lifetime and requests the cellular eNB to determine V2V links. The optimum resource allocation problem at the cellular eNodeB is to choose optimum receiver vehicles to determine V2V links and allocate suitable channels to minimize the total latency. In this paper, simulation results demonstrate that, the proposed scheme can improve the latency as the number of packets that successfully arrive at their destinations through multi-hop routes before their expiration time is increased. Moreover, the performance improvement increases as more dedicated channels are allocated by the cellular eNodeB or larger threshold $T_th$ is applied. In addition, it is confirmed that a moderate increase in the vehicle's speed can improve the network connectivity and hence, improve latency performance, but a large increase in speed may cause high latency and thus, increase the latency.

In another paper [5] author developed the decentralized resource allocation scheme for V2V communications based on deep reinforcement learning. According to the decentralized resource allocation scheme, a V2V link or a vehicle working as learning agent, makes its decisions to find the optimal sub-band and power level for transmission without requiring or having to wait for global information. This agents learned by decentralized deep Q-learning (DQN).

- State Space: $\{G_t, H_t, I_{t-1}, N_{t-1}, L_t, U_t\}$
  $G_t = \{G_t[1], ..., G_t[M]\}$: Channel gain between V2V link, in each sub-channel m
  $H_t = \{H_t[1], ..., H_t[M]\}$: Channel gain between V2I link, in each sub-channel m
  $I_{t-1} = \{I_{t-1}[1], ..., I_{t-1}[M]\}$: The previous interference power to the link.
  $N_{t-1} = \{N_{t-1}[1], ..., N_{t-1}[M]\}$: The selected of sub-channel of neighbours in the previous time slot.
  $L_t$: Remaining load to transmit.
  $U_t$: Remaining time to meet the latency constraints.
- Action Space: Resource Block allocation, Power level (High, Mid, Low) (Action space size = $3 * N_RB$)
- Reward: Sum capacity of V2I, Sum capacity of V2V, Penalty of the latency constraint.

Since the proposed methods are decentralized, the global information is not required for each agent to make its decisions, the transmission overhead is small. From the simulation results, each agent can learn how to satisfy the V2V constraints while minimizing the interference to V2I communications.

### B. Mode Selection Scheme

In paper [6] provides an efficient communication mode selection scheme. In this scheme, compare the calculated time delay between V2V and V2I protocols, then select an efficient protocol with the time delay as a performance metric. As a result, seamless connectivity issues in a vehicular ad-hoc network can be fixed by an efficient choice of a vehicular protocol between V2V and V2I. Such a decision is taken by each vehicle whenever it needs to transmit messages. However, short decision cycle causes high computational and switching overhead.

To solve this problem, the paper [7] proposed deep reinforcement learning (DRL)-based decentralized algorithm. By using this algorithm, we can maximize the sum capacity of V2I users while meeting the latency and reliability requirements of the V2V pair with low computational burden. In this algorithm V2V pairs are working as the learning agents and they learned by federate learning.

- State Space: Received interference power, Large-scale channel gain between V2V Tx, Rx.
- Action Space: RB allocation, mode selection (V2V mode, V2I mode), transmit power
- Reward: Sum capacity of V2I UE, Penalty of unsatisfied capacity for V2I UE, Impacts of the reliability and latency requirements.

Considering a large continuous value state space, a DRL-based decentralized algorithm has been designed to train the DRL model. In order to train robust DRL models and improve the performance of newly activated V2V pairs, a two-timescale federated DRL-based semi-decentralized algorithm has been further developed. The simulation results have demonstrated the superiority of the proposed DRL-based algorithm with different numbers of V2V pairs and outage thresholds, as well as the effectiveness of the proposed federated DRL algorithm for newly activated V2V pairs.

### C. Cell association Scheme

In the paper [8] investigates the problem of vehicle-cell association in millimeter wave (mmWave) communication networks. The aim is to maximize the time average rate per vehicular user (VUE) while ensuring a target minimum rate for all VUEs with low signaling overhead. The proposed scheme uses distributed deep reinforcement learning. All of the rode side unit (RSU) Cells are working as learning agent. And they learned by decentralized asynchronous actor critic (A3C) Algorithm

- State Space: {Last channel observations, Vehicles' required data rates, Received data rates.}
- Action Space: Each Road Side Unit (RSU) Cell selects the vehicle to provide the data.
- Reward: Sum average rate of all the vehicles, Penalty of the reliability constraint.

## V. Conclusion

To support the future automobile industry, V2X communication can achieve significant changes. (e.g., autonomous driving, road safety, and efficient traffic services) However there are strict latency requirements for safety-related V2X services and autonomous driving servies to run. The most strict requirements of V2X services are 10ms latency with the 1e-5 BER. V2X services face challenges due to stringent latency requirements, along with high reliability for V2X services. Thus, as we have seen in this paper, various approaches are under way to achieve URLLC in V2X communication. Although there has been an improvement in latency metric through each studies, further research is needed to meet the stringent latency requirements.

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